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Introduction

Controlling the vulnerability of embankment dikes is one of the main concern for river managers. Indeed, the failure of such dikes may have catastrophic socio-economic impacts including casualties for neighboring populations.

In France, thousands of kilometers of embankment dikes were insufficiently maintained in the past (Zanetti & al., 2010), leading to the development of woody vegetation on these embankments and their surroundings. Root growth in the fills generates significant risks, particularly a risk of internal erosion by piping. Internal erosion occurs when particles are torn off and transported along preferential pathways (CFGB, 1997) and is one of the main causes of dikes failure (Foster & al., 2000). It can be initiated by the presence of root systems that constitute areas of heterogeneity in the dike. Root decomposition creates areas of high permeability favoring infiltration and accelerating water flows (Zanetti & al., 2008). To assess the potential risk rate of pipe development with root decaying, or inside the root when wood decomposes while bark is preserved, the rate of roots decomposition with time should be analyzed (Vennetier & al., 2004) ; (Mériaux & al., 2006).

Most often, studies about wood decomposition aim at studying the production of biomass from forests or the relationships between carbon and nitrogen fluxes resulting from dead wood decomposition into belowground systems (Vogt & al., 1986). Most studies deal with decomposition of leaf litter (for example Olson, 1963) or root litter (Berg, 1984) close to soil surface. Studies assessing the rate of woody root decomposition in the soil are scarce especially due to the general technical difficulty in studying belowground processes (Chen & al., 2001). The study and monitoring of underground root decomposition can be achieved by different methods that depend especially on diameter class. Commonly used approaches are buried litterbags and trench plots or more rarely tethered roots and buried pots (Silver & Miya, 2001). Chemical analysis generally target C, N, lignin and polyphenol concentrations which are commonly used to characterize and predict decomposition stages (Creed & al., 2004; Goebel & al., 2011). So some authors as Aulen & al., (2012) used Near-Infrared spectroscopy (NIRS) to assess the chemical characteristics of root samples. Indeed, NIRS is commonly used to identify and predict wood physical and chemical properties (Poke & Raymond, 2006). NIRS presents a strong potential, comparable in efficiency to traditional chemiometric methods but with considerable time saving (Malkavaara & Raimo, 1998; Kelley & al., 2004; Jones & al., 2006). Indeed, near-infrared spectroscopy is faster, requires less sample preparation and may be non-destructive (Marten & al., 1989). Spectroscopic techniques allows investigation at molecular scale for complex samples, information on sample chemical composition and physical properties and possible interactions. NIRS was already successfully used to characterize and discriminate different trees species (Çetinkol & al., 2012).

Study goals

This study aims at contributing to the assessment of risk related to the presence of root systems and their decomposition in embankment dikes in order to help designing vegetation management plan. This paper focuses on the characterization of NIRS response of decaying roots from tree species frequently growing on embankment dikes. Root decomposition causing chemical and physical changes in the wood, it is important to characterize the variability of these changes as a function of decomposition time, tree species and root diameter.

Material and methods

Experimental device

In order to study root decomposition of various species in homogeneous conditions, an experimental device was laid out in 2008 on a dike of Isere River (Fig.1) (Caroline Zanetti & al., 2008).

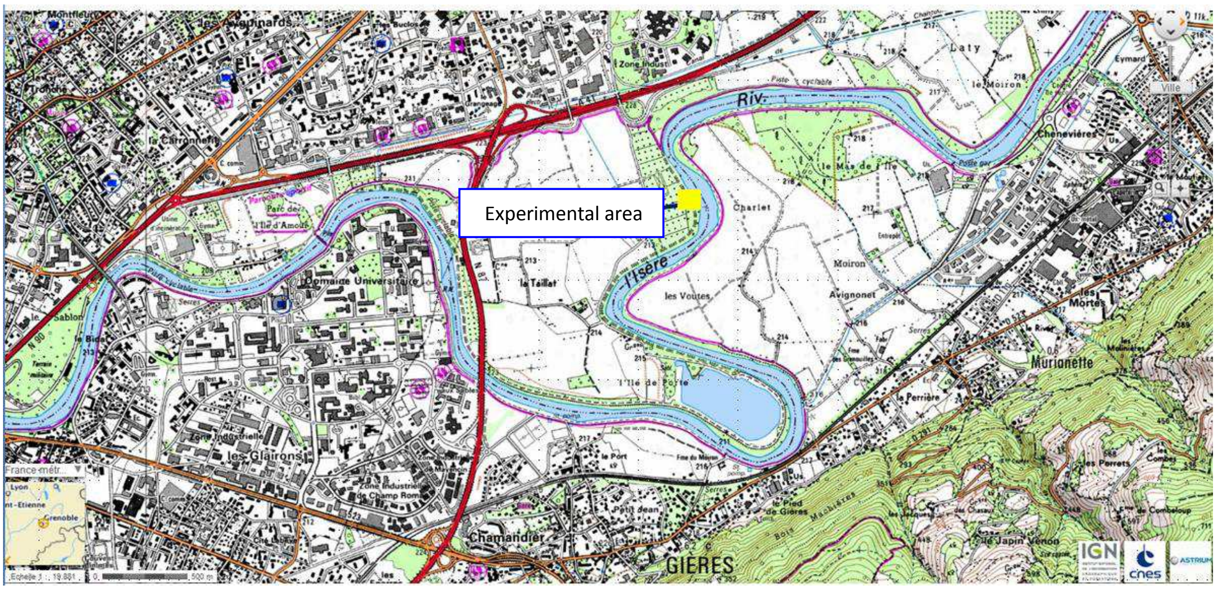

Fig. 1. Location of experimental area.

This old dike was built in the 19th century from non-compacted heterogeneous materials (a mixture of sand, gravel and silt in various proportions) and heightened between 1950 and 1970. Isère dikes are narrow (ridge 3-meter wide) with steep slopes covered up to recently by a dense forest stand (Pinhas, 2005). Therefore they are vulnerable to internal erosion caused by the presence and potential decay of large woody roots (Zanetti & al., 2009). Oak (*Quercus robur*), Ash (*Fraxinus excelsior*), Poplar (*Populus alba*) and Black Locust (*Robinia pseudoacacia*), the most frequent tree species on French dikes, were selected for the experiment. After tree logging, stumps were carefully extracted from dike slopes or ridge in order to preserve root systems for further investigation. Root samples (length = 20 cm, diameters 3, 5, 8 and 10 cm) were immediately cut from these stumps, laid out in stainless steel baskets and buried at 5O cm depth in the embankment (Fig. 2). The experiment has been designed for a 10-year long follow up of root decomposition, roots sample collection being scheduled every two or three years according to their evolution.

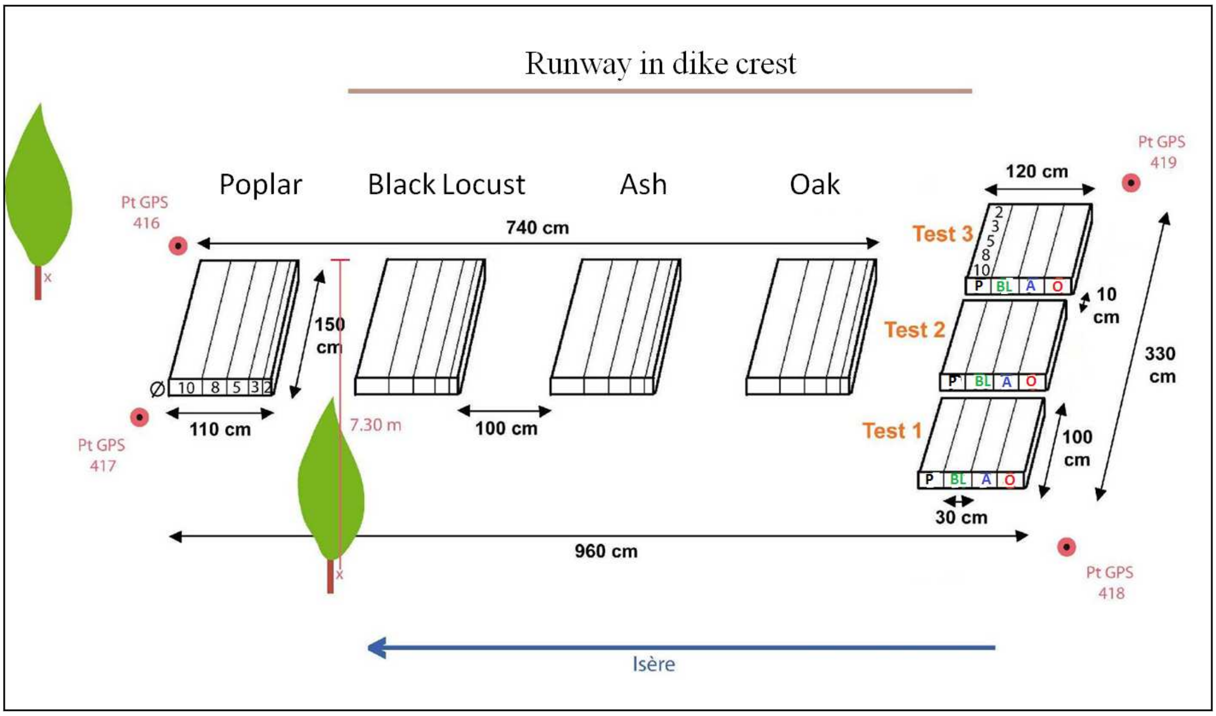

Fig. 2. Root decomposition experimental device.

In 2008, the first samples were analyzed in order to measure wood initial characteristics for each species and root diameter. To date, we successively analysed root samples at three steps of the decaying process: T0 (initial wood - 2008), T2 (2 years of decomposition - 2010) and T4 (4 years of decomposition - 2012).

Near-Infrared spectroscopy

We used a FT-NIR spectrophotometer, Thermo-Nicolet Antaris equipped with an interaction sphere (spectral range: 10000-4000cm^{-1}, 50 scans, 4 cm^{-1}). All samples were dried at room temperature (25°C) and then cut in slices with the same saw to obtain the required quantity of sawdust. For each species and diameter, three samples were used in order to obtain three spectra which were subsequently averaged (Fig.3). For chemometric study, all spectra were pretreated with a first derivative.

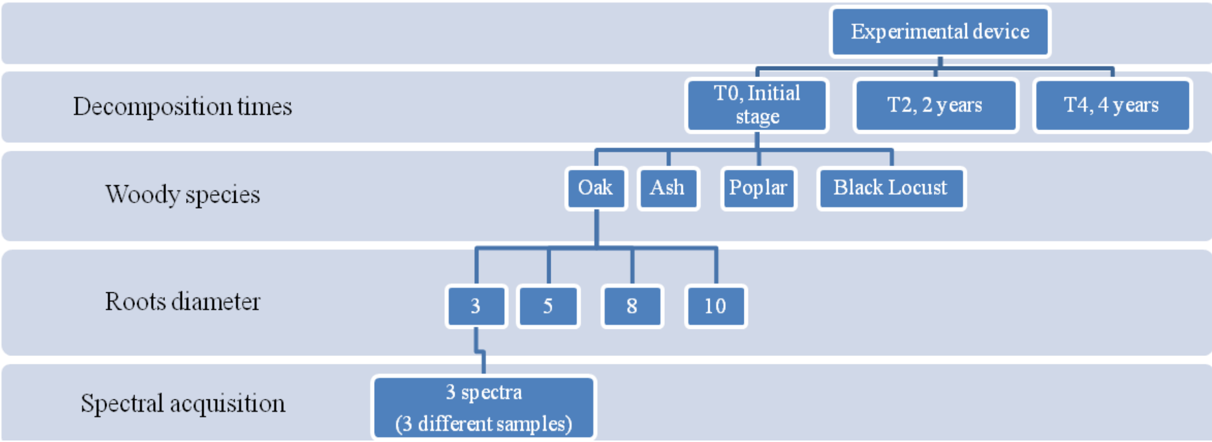

Fig. 3. Presentation of the different classes of samples.

The sample set is therefore composed of: 3 (three samples per diameter)* 4 (four diameter classes)* 4 (four tree species)* 3 (three decomposition time) = 144 samples.

Data processing: chemometric methods

PCA was used as a first step for exploratory data analysis to detect groups and investigate data structure.

PLS (Haaland & Thomas, 1988) was initially designed for quantitative analysis, but it is now also used for pattern recognition. This supervised analysis is based on the relation between spectral intensity and sample characteristics (Martens & Næs, 1989).

The prediction of decomposition times was performed with a PLS 1 model. Samples were split into two sets: 96 samples for calibration and validation (cross-validation) and the 48 remaining ones to test the predictive model. For each decomposition time, a PLS2-DA model was computed to predict tree species and root diameter simultaneously. The sample was then assigned to one class when the value was above a specific prediction threshold (Roussel & al., 2003).

To predict tree species, the output variable was transformed with a binary code: 1 for the samples belonging to the class and 0 to those not belonging to the class. Samples with predicted values between 0.5 and 1.5 were identified as belonging to the class and those with values out of these limits as not belonging to the class. Samples were again split into two sets: 32 to perform calibration and validation (cross-validation) and 16 to test model predictions. Models accuracy was assessed with performance indices: R^2 (calibration), SEC (standard error of calibration), bias (calibration), number of latent variables, R^2 (prediction), SEP (standard error of prediction) and bias (prediction). For discriminant analysis (PLS-DA), the confusion matrices allowed accessing the percentages of correct classification.

This chemometric study was conducted with the Unscrambler software version 9.8 from CAMO (Oslo, Norway).

Results and discussion

Exploratory analysis (Principal Component Analysis - PCA)

The PCA on NIRS spectra highlighted groups, subgroups, the dispersion within groups and spectral ranges of interest.

Separation of root decomposition times;

In the first plane of the PCA with all root samples (n = 144, Fig. 4) the three decomposition times (T0, T2, and T4) clearly gathered in 3 distinct groups and therefore constitute the first criterion to sort samples. The observed dispersion within groups was linked to the other sources of variability, particularly tree species and root diameter (Fig. 5). For all samples, the general trend with ageing seemed to be similar, regardless of tree species and diameter classes.

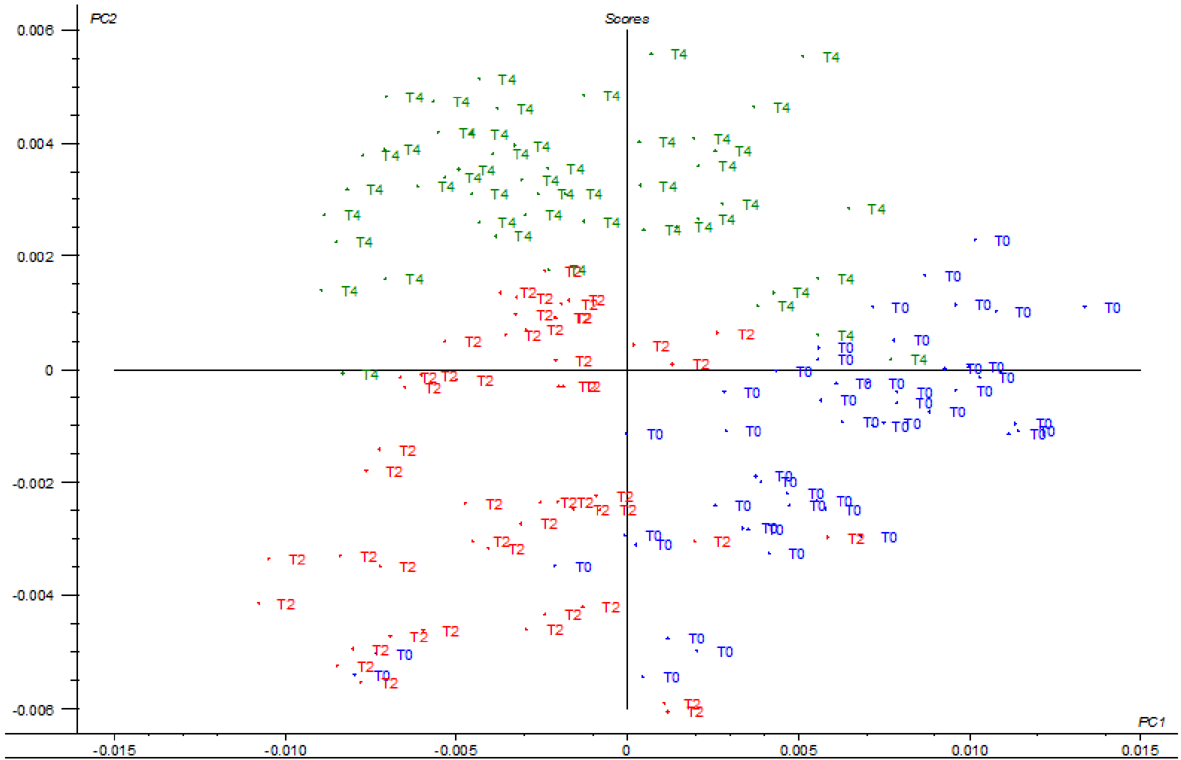

Fig. 4. Plan 1/2 of the PCA conducted on all samples (T0 = initial state, T2 = 2 year and T4 = 4 years, n = 144, explained variance = 78%).

Tree species and root diameter

The three PCA performed separately for each decomposition time (T0, T2 or T4) highlighted groups corresponding to the four tree species: oak, ash, poplar and black locust and subgroups related to the four diameter classes. There are significant differences in chemical composition and physical properties between tree species and for each species between the different diameters at all decomposition times. However, the more samples are ageing (after four years of decomposition), the less the variability between diameters. On figure 5 showing the PCA performed at decomposition times T0, a good separation between tree species, as well as between diameter classes within each species was obtained in the plane of main components 3 and 6. Species constitutes the second discrimination criterion (after decomposition time) except for black locust which diameter class 3 stands apart from the rest of the species area. Root diameter is the third criterion.

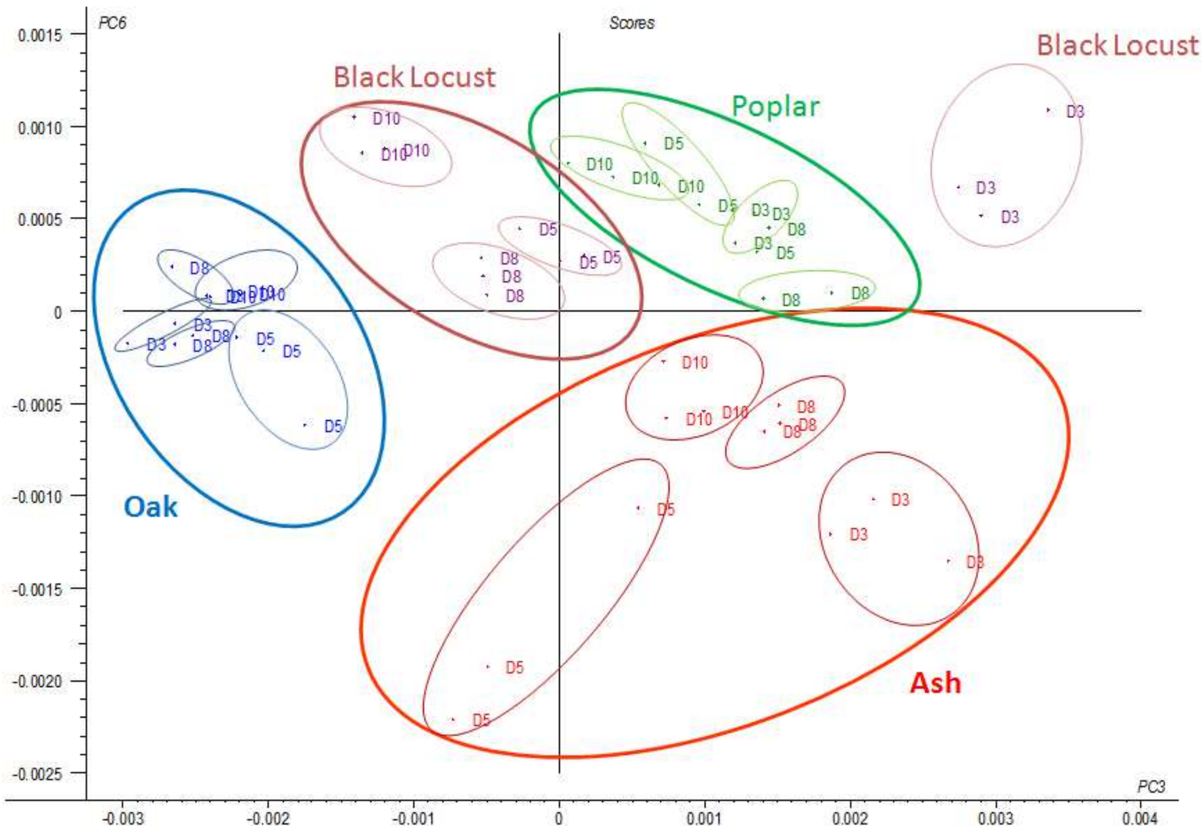

Fig. 5. Plan 3/6 of the PCA conducted on woody species and diameter classes at decomposition times T0 (Blue = Oak, red = Ash, green= poplar, purple = Black Locust, D3=diameter 3, D5=diameter 5, D8=diameter 8, D10=diameter 10, n = 48, explained variance = 9%).

Predictive analysis (Partial Least Square Regression – PLS regression)

The goal of this analysis was to calibrate the model in order to further assess its ability to differentiate unknown root samples belonging to different species.

Prediction of root decomposition times (PLS1)

The PLS-1 model allowed predicting the decomposition time with a good correlation (R^2), an error of prediction (SEP) and a low bias (Table 1).

Table 1. Statistics for the predictive model of decomposition times (PLS1).

	NIR
Decomposition Times	T0, T2 and T4
Factor number	6
R^2 (Calibration)	0,981
SEC	0,314
Bias (Calibration)	- 7,45.10^{-8}
R^2 (Prediction)	0,952
SEP	0,506
Bias (Prediction)	0,016

R^2: coefficient correlation, SEC: Standard Error of Calibration, SEP: Standard Error of Prediction

In the prediction model, the three following margins were considered for acceptance:

- For T0, -1 to 1; for T2, 1 to 3; for T4, 3 to 5.

Two T0 samples were predicted as T2; one T2 sample was predicted as T0; and one T4 sample was predicted as T2. Finally, only 4 samples among 48 were misclassified, less than 10%.

This shows the good accuracy of the model for predicting decomposition time of unknown samples.

Prediction of woody species and the diameter of roots (PLS2-DA)

The PLS2-DA models allowed predicting tree species and diameter for each of the three decomposition times with a good correlation (R^2), few errors of prediction (SEP) and low bias (Table 2). Concerning tree species, the model led to an accurate prediction (Table 3).

When comparing statistics of the three models, prediction for oak and black locust became slightly less accurate for T2 and T4 than for T0. For poplar, we did not observe significant variations between the different decomposition times. Finally, we observed a decrease in prediction accuracy of ash between T2 and T4.

The confusion matrix for tree species showed that only three samples were misclassified. The prediction considered successively each species compared to all other ones ("other"). No classification error was found for T0. For T2, one "other" (ash) sample was predicted as an oak and one poplar sample was classified as "other". For T4, one oak sample of was classified as "other".

These good results showed that even after 4 years of decomposition and a degraded physical structure, species still display significantly different chemical composition and physical characteristics.

Tableau 2. Statistics for the predictive models (PLS2-DA) of roots diameter and woody species for each decomposition times.

	NIR				
	T0				
Predicted variables	Diameter	Oak	Ash	Poplar	Black Locust
Factor number	8	8	8	8	8
R^2 (Calibration)	0,999	0,974	0,953	0,983	0,951
SEC	0,110	0,099	0,133	0,081	0,136
Bias (Calibration)	$- 5,96.10^{-8}$	$3,26.10^{-9}$	$- 3,26.10^{-9}$	$- 3,72.10^{-9}$	$4,66.10^{-9}$
R^2 (Prediction)	0,863	0,972	0,858	0,952	0,914
SEP	1,406	0,107	0,246	0,140	0,194
Bias (Prediction)	0,224	0,020	-0,001	-0,008	-0,011
	T2				
Predicted variables	Diameter	Oak	Ash	Poplar	Black Locust
Factor number	8	8	8	8	8
R^2 (Calibration)	0,997	0,931	0,938	0,965	0,921
SEC	0,208	0,160	0,152	0,116	0,171
Bias (Calibration)	$5,21.10^{-8}$	$5,59.10^{-9}$	$- 6,98.10^{-9}$	$- 1,21.10^{-8}$	$6,05.10^{-9}$
R^2 (Prediction)	0,810	0,846	0,861	0,928	0,845
SEP	1,652	0,240	0,243	0,178	0,246
Bias	0,436	0,051	0,010	-0,068	0,007
	T4				
Predicted variables	Diameter	Oak	Ash	Poplar	Black Locust
Factor number	7	7	7	7	7
R^2 (Calibration)	0,997	0,904	0,829	0,974	0,905
SEC	0,200	0,188	0,246	0,100	0,187
Bias (Calibration)	$1,34.10^{-7}$	$1,72.10^{-8}$	$- 1,72.10^{-8}$	$- 1,40.10^{-9}$	$8,85.10^{-9}$
R^2 (Prediction)	0,787	0,860	0,788	0,955	0,887
SEP	1,885	0,242	0,294	0,134	0,223
Bias (Prediction)	0,011	-0,012	-0,002	-0,001	0,015

R^2: coefficient correlation, SEC: Standard Error of Calibration, SEP: Standard Error of Prediction

Table 3. Confusion matrix for the woody species variables at decomposition times T0, T2 and T4 from the predictive model PLS2-DA regression (Models: First derivative as pre-treatment).

		Predicted classes - NIR					
		T0		T2		T4	
Prediction Oak		Oak	Others	Oak	Others	Oak	Others
Real classes	Oak (n=4)	4	0	4	0	3	1
	Others (n=12)	0	12	1	11	0	12
Prediction Ash		Ash	Others	Ash	Others	Ash	Others
Real classes	Ash(n=4)	4	0	4	0	4	0
	Others (n=12)	0	12	0	12	0	12
Prediction Poplar		Poplar	Others	Poplar	Others	Poplar	Others
Real classes	Poplar(n=4)	4	0	3	1	4	0
	Others (n=12)	0	12	0	12	0	12
Prediction Black Locust		Black Locust	Others	Black Locust	Others	Black Locust	Others
Real classes	Black Locust (n=4)	4	0	4	0	4	0
	Others (n=12)	0	12	0	12	0	12

Discussion

Although tree roots used in this study present much variability, we demonstrated the interest of NIRS and PLS models to study and predict with a good accuracy a complex set of characteristics including wood decomposition time, tree species and root diameter. Indeed the total number of samples (144) was enough for the study of decomposition time but the number of samples for each diameter within each species was limited. However, the high level of success in sample classification in all analysis demonstrated that the method was worth being developed and validated on other sites with the same species and with other species, and more numerous samples.

For the first time, we showed that it was possible to discriminate three levels of variability in wood with a single NIRS analysis, unlike previous studies such as for example Çetinkol & al. (2012) which focused on only one source of variation, tree species or wood decomposition time. Moreover, there is scant literature on large tree root decomposition, none of these papers including NIRS. Most studies using NIRS analyzed the evolution of chemical traits during fine roots decomposition (Aulen & al., 2012). Tree root evolution for diameters larger than 2 cm is generally assessed by density loss (Chen & al., 2001; Ludovici & al., 2002). We also used density loss especially with the X-ray tomography on the same samples (Zanetti, 2010), showing that decomposition time was easy to assess. But NIRS allowed discriminating samples from their physical and chemical characteristics and seems to be an innovative approach to the study large tree roots decomposition.

Root separation by diameter in NIRS spectra can be explained by the strong correlation between root diameter and age (Zanetti & al., 2010). During root aging, as for tree trunk, a central zone of heartwood appears and develops regularly. For diameter class 2, no or very few heartwood was found in our samples. For larger roots, heartwood proportion increases with diameter up to more than 50%. Heartwood is formed when wood cells die and are filled with various compounds aiming at increasing their strength and their resistance to parasites and diseases (fungus, insects, bacteria, etc.). These chemical and physical changes in cells result in significant variations of NIR spectra.

Conclusion

This study showed that the Near-Infrared spectroscopy (NIRS) presents high potential for the study of woody roots growing in earth dikes. The analysis of NIRS spectra by chemometric tools and PLS models allowed discriminating and predicting the decomposition times (0 to 4 years), tree species and root diameter. Compared to traditional methods (density, X-rays tomography, chemical analysis), these models may allow a simpler, faster and reliable assessment at low cost. Provided that it is validated on other species and regions, this method could help river managers to design appropriate maintenance and management plans to ensure the reliability of embankment dikes.

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References

Aulen, M., Shipley, B., & Bradley, R. (2012). Prediction of in situ root decomposition rates in an interspecific context from chemical and morphological traits. *Annals of Botany*, *109*(1), 287–297.

Berg, B. (1984). Decomposition of root litter and some factors regulating the process: Long-term root litter decomposition in a scots pine forest. *Soil Biology and Biochemistry*, *16*(6), 609–617.

Çetinkol, Ö. P., Smith-Moritz, A. M., Cheng, G., Lao, J., George, A., Hong, K., Holmes, B. M. (2012). Structural and Chemical Characterization of Hardwood from Tree Species with Applications as Bioenergy Feedstocks. *PLoS ONE*, *7*(12).

CFGB. (1997). Internal erosion: typology, detection, repair. In *Comité Français des Grands Barrages, Florence, ITA, mai 1997* (Vol. -, p. 126).

Chen, H., Harmon, M. E., & Griffiths, R. P. (2001). Decomposition and nitrogen release from decomposing woody roots in coniferous forests of the Pacific Northwest: a chronosequence approach. *Canadian Journal of Forest Research*, *31*(2), 246–260.

Creed, I. F., Webster, K. L., & Morrison, D. L. (2004). A comparison of techniques for measuring density and concentrations of carbon and nitrogen in coarse woody debris at different stages of decay. *Canadian journal of forest research*, *34*(3), 744–753.

Foster, M., Fell, R., & Spannagle, M. (2000). The statistics of embankment dam failures and accidents. *Canadian Geotechnical Journal*, *37*(5), 1000–1024.

Goebel, M., Hobbie, S. E., Bulaj, B., Zadworny, M., Archibald, D. D., Oleksyn, J., … Eissenstat, D. M. (2011). Decomposition of the finest root branching orders: linking belowground dynamics to fine-root function and structure. *Ecological Monographs*, *81*(1), 89–102.

Haaland, D. M., & Thomas, E. V. (1988). Partial least-squares methods for spectral analyses. 1. Relation to other quantitative calibration methods and the extraction of qualitative information. *Analytical Chemistry*, *60*(11), 1193–1202.

Jones, P., Schimleck, L., Peter, G., Daniels, R., & Clark, A. (2006). Non destructive estimation of wood chemical composition of sections of radial wood strips by diffuse reflectance near infrared spectroscopy. *Wood Sci Technol.*, *40*, 709–720.

Kelley, S., Rials, T., Groom, L., & Sluiter, A. (2004). Use of near infrared spectroscopy to measure the chemical and mechanical properties of solid wood. *Wood Sci Technol.*, (38), 257–276.

Ludovici, K. H., Zarnoch, S. J., & Richter, D. D. (2002). Modeling in-situ pine root decomposition using data from a 60-year chronosequence. *Canadian Journal of Forest Research*, *32*(9), 1675–1684.

Malkavaara, P., & Raimo, A. (1998). A spectroscopic method for determining lignin content of softwood and hardwood karft pulps. *Chemometrics and intelligent Laboratory Systems*, *44*, 287–292.

Marten, G. C., Shenk, J. S., Barton, F. E., & Service, U. S. A. R. (1989). *Near infrared reflectance spectroscopy (NIRS): analysis of forage quality*. U.S. Dept. of Agriculture, Agricultural Research Service.

Martens, H., & Næs, T. (1989). *Multivariate calibration*. Wiley.

Mériaux, P., Vennetier, M., Aigouy, S., Hoonakker, M., & Zylberblat, M. (2006). Diagnosis and management of plant growth on embankment dams and dykes. (pp. 1–20). Presented at the Vingt-deuxième Congrès des Grands Barrages, Barcelone.

Olson, J. S. (1963). Energy Storage and the Balance of Producers and Decomposers in Ecological Systems. *Ecology*, *44*(2), 322–331.

Pinhas, M. (2005). Confortement de digues étroites et boisées : le cas des digues de l'Isère. *Ingénieries-EAT, n°Spécial Sécurité des digues fluviales et de navigation*, pp. 179–184.

Poke, F. S., & Raymond, C. A. (2006). Predicting Extractives, Lignin, and Cellulose Contents Using Near Infrared Spectroscopy on Solid Wood in Eucalyptus globulus. *Journal of Wood Chemistry and Technology*, *26*(2), 187–199.

Roussel, S., Bellon-Maurel, V., Roger, J.-M., & Grenier, P. (2003). Authenticating white grape must variety with classification models based on aroma sensors, FT-IR and UV spectrometry. *Journal of Food Engineering*, *60*(4), 407–419.

Silver, W. L., & Miya, R. K. (2001). Global patterns in root decomposition: comparisons of climate and litter quality effects. *Oecologia*, *129*(3), 407–419.

Vennetier, M., Chandioux, O., & Ripert, C. (2004). Diagnostic et gestion de la végétation sur ou dans l'environnement des digues (pp. 551–567). Presented at the Colloque technique CFGB MEDD, Sécurité des digues fluviales et de navigation, Orléans.

Vogt, K. ., Grier, C. ., & Vogt, D. J. (1986). Production, turnover, and nutrient dynamics of above- and below-ground detritus of world forest. *Advances in Ecological Research*, *15*, 303–366.

Zanetti, C., Guibal, F., Brugier, M., Vennetier, M., Mériaux, P., & Provansal, M. (2010). Growth characterization of woody roots on river dikes. *Collection EDYTEM*, (11), 115–122.

Zanetti, C. (2010). *Caractérisation du développement des systèmes racinaires ligneux dans les digues*. Université de Provence, Aix-en-Provence.

Zanetti, C., Mériaux, P., Vennetier, M., & Royet, P. (2010). Colonisation par les arbres des petits barrages ou digues de canaux en terre : diagnostic et consignes d'entretien au travers d'études de cas. Presented at the Colloque CFBR - AFEID "sécurité des barrages et nouvelle règlementation française - Partage des méthodes et expériences," Lyon.

Zanetti, C., & Vennetier, M. (2009). *Etude de l'enracinement des arbres dans les digues de protection contre les crues de l'Isère* (Rapport d'étude) (p. 38). Aix-en-Provence, France: Cemagref.

Zanetti, C., Vennetier, M., Mériaux, P., Royet, P., Dufour, S., & Provansal, M. (2008). L'enracinement des arbres dans les digues en remblai: étude des systèmes racinaires et impacts sur la sécurité des ouvrages. *Ingénieries-EAT*, (53), 49–67.